Photonic Band Gap Materials-Theory, Techniques and Application

Immad Girach, Muhammad I. Aslam, Irfan Ahmed, Syed M. Usman Ali and Muhammad Khalid

***Abstract*— Photonic Band Gap (PBG) materials are a relatively new frontier for research that allow for control of the propagation of EM waves in desired directions and at desired frequencies. The PBG materials essentially have periodic refractive index in one-, two-, or three- dimensions in the order of wavelength of the EM wave. These PBG materials take advantage of the interaction of Photons with the periodicity of the dielectric materials. Due to periodic nature certain band gap exists in the material and photons at frequencies corresponding to the band gap (or stop band) are forbidden to pass through the material. After its inception almost three decades back, extensive research has been carried out in this domain and various structures have been proposed that are able to interact with light at Photon level and produce astonishing results. They are also a perfect solution for high-frequency operation since metallic waveguides tend to be lossy at higher (especially optical) frequencies. In this paper, a review shall be presented encompassing important aspects of PBG materials including their structures, properties, potential applications, available tools for their analysis and future research trends.**

***Index Terms*— Band Gap Materials; Electromagnetics; Light wave; Photonic Crystals; Photonic Band Gap**

I. Introduction

Human instinct of curiosity and lust for knowledge has led us to numerous inventions to facilitate human living and provide innovative solutions to our problem in various fields of life. Most interesting inventions that revolutionized our world in the past century are semiconductor-based devices. An important property of Semiconductors is existence of an energy bandgap. Electrons may exist in lower energy states (valance bands) or in higher energy states (conduction bands) as compare to the bandgap but no electron possesses the band gap energies [1]. Utilizing the bandgap the flow of current (electrons) may be controlled leading to many useful devices such as diodes, transistors etc. [2].

Studies have shown that the similar behavior can be observed for electromagnetic (EM) waves as well. Although physicists were aware of the existence of these materials long ago [3], but the pioneering work by Sajeev John and Eli Yablonovitch [4,5] sparked extensive research in this field [6-8]. Various materials have been proposed to exhibit photonic bandgaps (PBG) where a photon existence is prohibited. Photons with higher or lower energy (which is proportional to its frequency) as compared to PBG may exist. Figure 1 shows an example of dispersion relation of a PBG material (generally known as photonic crystals). It can be observed that some frequencies (ω) does not correspond to any of the wavenumber (k) thereby representing a bandgap. These materials provide the opportunity to interact and control flow of EM waves (more specifically photons) as a semiconductor does for electrons.

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This paper provides a brief review of PBG materials, their properties and types. We also provide a summary of research trends in this fast growing field and potential applications of PBG materials. Moreover, we summarize various analytical and numerical tools that are available to design and analyze their behavior.

Rest of the paper is organized as follows. Section II provides an overview of types on properties of PBG materials. Section III is a summary of potential applications of PBG materials. Section IV reviews some of the available analysis and design tools. Section V provides a brief account of Photonic Crystal Fibers (PCF) which is an important and telecommunication applications of photonic crystals. Section VI concludes the paper.

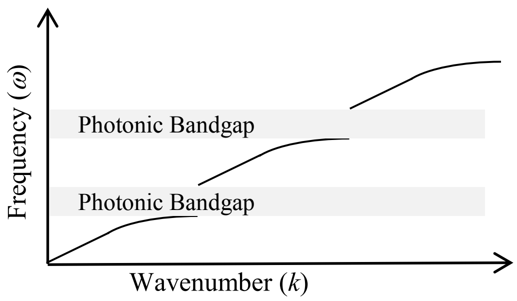

Fig. 1. An example of dispersion relation (i.e. ω-k relation) in arbitrary units of a PBG material. Bandgaps are indicated in the figure.

II. Photonic Band Gap materials

Photonic crystals are essentially periodic nanoscale structures that interact with light particles (photons) in the same way as electrons with a semiconductor material. Generally, photonic crystals are made of regularly repeating regions of two different dielectric materials (having different relative permittivity) [9]. However, researchers have proposed other structures such as metalo-dielectric structures or semiconductor structures. Natural opals and certain butterfly wings are examples of the formation of photonic crystals in nature. They are known to exhibit reflection of certain wavelengths of light at certain angles due to their periodic nature. This phenomenon can be seen

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when we see natural opal crystal with different view angles and iridescent colors are seen as we change the views [10].

A. How band gap occurs?

A deeper insight of the physics involved with the PBG phenomenon shows that at the bandgap the material undergoes scattering resonance. Two types of scattering takes place for such materials: one is macroscopic and other is microscopic scattering resonance. Microscopic scattering occurs when EM waves strike the unit cell of the crystal lattice while macroscopic scattering is due to the effect of multiple lattice units as a whole on the EM wave when it strikes them. Secondly the two scattering resonances should occur for the same wavelength and should be very strong. Thirdly, the material should exhibit minimum intrinsic absorption for the respective frequencies [11]. The overall affect results in blocking of propagation of EM waves at specific frequencies resulting in a bandgap as represented in the illustration of transmission spectrum of Figure 2.

B. Classification of Photonic Crystals

Photonic crystals are classified as 1D, 2D or 3D on the basis of dimensions in which periodicity occurs. For example, if a wave travelling in a particular direction in the material (say along *z*-axis), experiences periodicity in *z*-direction only, the material is said to be 1D PBG material, if it experiences periodicity of refractive index along *x*- and *y*- axis but not in *z*-axis, the material is said to be 2D PBG. Lastly, if the wave undergoes periodicity of refractive index along all three axes, it is said to 3D PBG material [9]. The pictorial representations of figure 3, illustrates three types of photonic crystals.

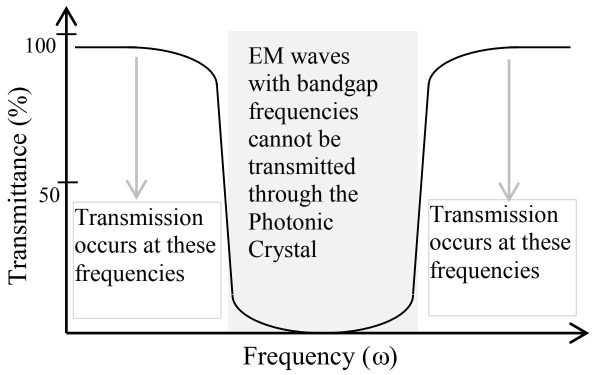

Fig. 2. Illustration of transmission spectrum of a PBG material. Transmission of EM waves at the bandgap frequencies are blocked by the photonic crystal.

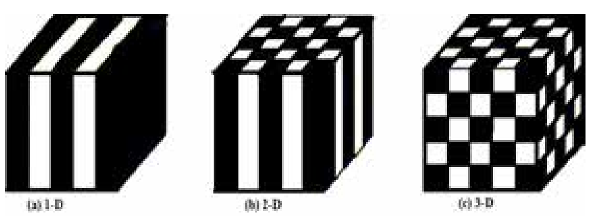

Fig. 3. Types of photonic crystals. (a) 1-D, (b) 2-D, (c) 3-D photonic crystals have periodicity in one-, two-, and three- dimensions respectively. Black and white colors in the figure respectively represent materials of high and low permittivity.

III. Potential PBG Applications

The properties of a photonic crystal depend on the geometry of the periodic structure and the index contrast of two materials used. Hence, by controlling these two parameters, properties of a photonic crystal can be controlled hence providing control over flow of light through the crystal [12]. Control over light to guide it along particular pathways has spurred global research into these materials paving the way for ground-breaking realities that existed only in theories of the past [9]. Numerous applications of PBG materials have been proposed in microwave as well as optical regime of EM spectrum. These applications include (but not limited to) high-Q micro-cavities [13,14], Efficient light sources [15], low-loss bent waveguides [16,17], Efficient filters [18], multiplexer and demultiplexer [19,20], photonic crystal fibers [17,21], Optical routers [22], radio frequency antennas [23], negative refraction [24], perfect lens [25], photonic /optoelectronic integrated circuits [14,26]. In section V of this review, we provide a brief account of only one PBG application (i.e. PCF) that is related to our current research focus.

IV. Analysis of PBG

In general, interaction of EM waves with a material is governed by Maxwell's equations. Therefore PBG materials can be well analyzed by solving Maxwell's equations. However, in most case it is impossible to solve these equations analytically. Although behavior of many types of photonic devices can be predicted by a simple analytical technique known as coupled-mode theory [9], most of the research rely on analytical techniques in this regard [27].

As a walkthrough of the method, the material is divided into smallest fundamental units of the lattice and converted to irreducible Brillouin zones. Then Bloch's theorem is applied for the zones and Maxwell's equations are tailored to form an eigenvalue problem. The eigenvalue problems is then solved numerically by one the many available methods to get the propagating modes and the dispersion relation. This way Bloch modes of the waves are found and dispersion relation of the crystal is calculated. This characterizes the crystal and reveals its frequency response over the desired frequency range [28]. Figure 4 shows a simplified flow chart to show steps involved in numerical analysis of a photonic crystal.

An important step in the analysis of photonic crystals is the solution of eigenvalue problem arising from Maxwell's equations. Following numerical techniques are commonly used in the analysis.

A. Finite Element Method (FEM)

FEM method is very flexible in which the computational domain is divided into smaller subdomains and then simple functions are used to estimate the unknown filed over each subdomain. Popular software packages based on FEM method are COMSOL Multiphysics, Lumerical mode solutions, and Ansoft HFSS.

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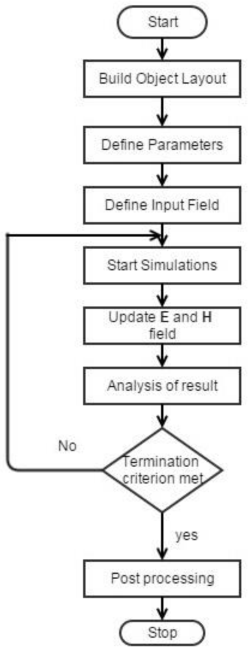

Fig. 4. Flow chart representing steps of numerical analysis of photonic crystals.

B. Finite-Difference Time-Domain Method (FDTD)

In FDTD method differential equations are approximated to finite difference equations to estimate derivatives. Modern FDTD analysis is generally based on Lee's algorithm [29]. Popular FDTD-based software packages are MIT Photonic Bands (MPB), OptiFDTD, MEEP, Lumerical FDTD solutions.

C. Finite-Difference Frequency-Domain (FDFD)

In FDFD, approximations are made on the wave vector in the frequency domain to numerically solve Maxwell's equations

D. Finite Integration Technique (FIT)

In FIT, Maxwell's equations are solved in integral form by using a spatial discretization scheme. This method is applicable to many EM problems. CST studio suite is popular software package utilizing this technique.

E. Plane-Wave Method (PWM)

PWM is popular method to calculate band structure of photonic crystals. The solution is obtained by expansion filed in number of plane waves.

F. Transfer Matrix Method (TMM)

TMM method makes layer-by-layer computation of a finite-thickness PBG material in the *k*-space.

G. Multiple Scattering Theory (MST)

The MST uses the analytical solutions of individual objects to calculate the effects of their interaction.

V. Photonic Crystal Fibers

As discussed earlier, a PBG material with a line defect forms a waveguide. In a nutshell, when this line defect is used to create long lengths of fibers for transporting light (also energy!), they are called photonic crystal fibers. While those with a line defect in a plane of material are there too, called planar photonic bandgap waveguides.

Photonic Crystal fibers have a uniform cross section along the fiber length, made up with two or more materials arranged micro structurally and periodically and in a cross-sectional manner. This micro-structured arrangement acts as a cladding around the core. Because of its ability to confine light in hollow/solid cores, characteristics not possible in conventional optical fiber have been attained. General categories of PCF include photonic-bandgap fiber (PCFs that confine light by band gap effects), holey fiber (PCFs using air holes in their cross-sections), hole-assisted fiber (PCFs guiding light by a conventional higher-index core modified by the presence of air holes), and Bragg fiber (photonic-bandgap fiber formed by concentric rings of multilayer film). They can also be described as 2D case of 3D photonic materials.

As far as mechanism of propagation is concerned, there are two basic mechanisms. First type is Photonic bandgap guidance which takes place when the refractive index of micro-structured cladding is higher versus core, this confines light to the air-core (or even vacuum-core) as light is unable to penetrate into the PBG cladding [30]. For this to take place distance between the holes (called pitch) is kept low. Second mechanism is a kind of modified total internal reflection. The effective index of micro-structured cladding is made lower than the solid core, hence the micro-structured holes act as cladding and light undergoes modified form of TIR. This is because light experiences lower refractive index at interaction with carefully planned geometry of the cladding and remains tightly confined to the core [31].

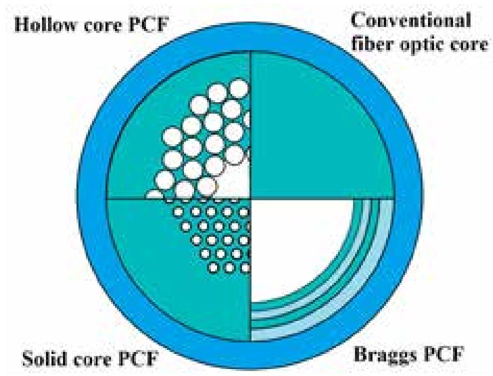

Fig. 5. A 4-in-1 logical diagram to show comparison of cores of 3 types of PCF and conventional fiber. White areas show air/vacuum areas while different colored areas indicate solid material with different refractive indices. Outermost rings shows conventional fiber cladding. (Not to scale!)

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VI. CONCLUSION

We present a review of PBG materials which exhibit prohibited band for the propagation of photons (EM wave) thereby allowing control over the propagation of EM waves through them bearing an analogy to behavior of electrons in semiconductor materials. These materials have numerous potential applications attracting attention of many research groups in this field. Moreover, we provide a brief account of PCFs that have potential of achieving superior properties compared to conventional optical fibers. The properties of PCF can be varied by changing the geometry of periodic structure and/or the physical material of the fiber.

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